



# **IMPROVING FUTURE CLIMATE PREDICTION USING PALAEOCLIMATE DATA**

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# IMPROVING FUTURE CLIMATE PREDICTION USING PALAEOCLIMATE DATA

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This White Paper represents an outcome of “The Leverhulme Climate Symposium 2008 - Earth’s Climate: Past, Present and Future”, convened by H. Elderfield, M. Bickle, G. Allen and E. Shuckburgh, and held at the University of Cambridge and the Royal Society, London, 10th - 13th March 2008.

Information on the Symposium is available at <http://www.leverhulmeclimatesymposium.org/>. Knowledge of past climate change can be used to improve our understanding of future climate change, but the full benefits of this archive have yet to be realised. The Symposium focused on determining what lessons from the past can be used to inform the future. This document builds on that objective and discusses how improved future climate prediction may be achieved using palaeoclimate data.

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## EXECUTIVE SUMMARY

The Fourth Assessment Report (AR4) of the IPCC identified many aspects of the climate system where future prediction remains highly uncertain. Addressing this uncertainty is critical for UK and international planning of climate adaptation and mitigation strategies. In many cases, this uncertainty arises from the lack of observations of relevant processes or changes in the short instrumental record. In such cases, palaeoclimate provides the ability to extend knowledge of climate behaviour and therefore to improve future predictability.

Part A of this White Paper outlines the potential of palaeoclimate research for improving our fundamental understanding of the climate system and its sensitivities. It identifies research approaches required to make progress in the field, and makes recommendations for specific future UK activities.

Three key research approaches are identified to enable palaeoclimate data to improve future prediction:

- i. Proxies used for palaeoclimate reconstruction need to be better calibrated, with a particular emphasis on assessing the uncertainty in their use. This effort should involve appropriate modelling, particularly the forward modelling of proxies in climate models;
- ii. Model-data comparison can be greatly enhanced by the specialist synthesis of palaeoclimate data;
- iii. Uncertainty in future predictions can be improved by testing models against the wide range of climate behaviour observed in the past.

Four recommendations are made for the embedding of palaeoclimate research within research programmes of the NERC themes:

- i. The development of a clear NERC strategy for palaeoclimate data synthesis, potentially involving establishment of a synthesis centre to build and maintain high-quality synthesis products and relevant synthesis expertise;
- ii. The routine use of palaeoclimate data to challenge the capabilities of UK global and regional climate models, and to improve prediction uncertainty from these models;
- iii. Explicit inclusion of questions motivated by palaeoclimate into new Climate and Earth System Science research programmes and the formal co-ordination of this work within the research programme structure;
- iv. Enhancing opportunities for cross-disciplinary training to bring together model and data expertise within the UK, and to combine expertise in current and past climate.

Part B of this White Paper identifies eight particular areas where palaeoclimate data can address uncertainties identified by IPCC in AR4. These include changes in rainfall, the carbon cycle, sea-level, ocean circulation, and extreme events. Most have significant implications for future regional climate in Europe and elsewhere. In each of these eight areas we describe past successes of palaeoclimate in contributing to the climate change agenda and in addressing questions relevant to future climate. And we identify productive areas for future research that will enable palaeoclimate research to make significant contributions to future climate prediction.

# PART A: THE BIG PICTURE

## A1. INTRODUCTION

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) produced a consensus view of knowledge about future climate change. It summarizes the effects of increasing atmospheric CO<sub>2</sub> levels on recent and future climate including expected warming and sea level rise during the 21st Century. Some such changes are now considered to be robustly known and have small uncertainties (Solomon et al., 2007). The AR4 also identifies a number of areas where our ability to predict the future is much less certain. These include aspects of the climate system of critical importance to society, such as the pattern and flux of future precipitation, changes in ice-sheets and sea level, and climate system components that exert a strong control on the pattern of regional climate such as El Nino – Southern Oscillation (ENSO). These uncertain aspects of future climate limit our ability to plan adaption and mitigation strategies, and prevent thorough cost-benefit analysis as countries plan international co-operation to reduce emission of greenhouse gases. Reducing uncertainty on such aspects of future climate change is therefore a highly desirable goal.

Palaeoclimate research offers a range of tools that can reduce uncertainty on future predictions. Reconstruction of the climate system in periods prior to instrumental records is possible using chemical, biological, and physical proxies that respond to environmental conditions. These proxies can provide information on climate variability that cannot be provided by direct observation of the modern climate. They can, for instance, show us how ‘slow’ components of the climate system such as ice sheets and the terrestrial biosphere respond to change on timescales longer than we have been measuring. And they can demonstrate behaviour in the climate system that has not been observed during short instrumental records.

Palaeoclimate data has contributed significantly to today’s climate change agenda. It was an interest in past climate that led to the first attempt to quantify the average global temperature change associated with a doubling of CO<sub>2</sub> (Arrhenius, 1896). Since then, palaeoclimate data has increasingly provided valuable insights into how the climate system operates on a range of timescales that cannot be captured by the 150 years of historical meteorological data. For instance, the relationship between climate change and CO<sub>2</sub> on glacial-interglacial timescales (Fig. 1), first actually observed in ice-cores in 1980 (Berner et al., 1980), played a large role in convincing scientists of the capability of CO<sub>2</sub> to warm the planet. Ice-core palaeo data was also the first to demonstrate the ability of the climate system to undergo rapid, large-amplitude, “abrupt” climate change (Fig. 1). Sediment core data has demonstrated that changes in ocean circulation are associated with these abrupt changes and has led to today’s close monitoring of ocean overturning. And coral and other geological data have shown that sea level can be significantly above the modern value in conditions only slightly warmer than today, providing a valuable insight into what stabilization of radiative forcing might mean for the future. Other examples of the power of palaeoclimate are provided in Table 1.

Focused application of palaeoclimate data to areas of uncertainty identified in the IPCC AR4 has the potential to reduce that uncertainty. Palaeo data can be used to assess and refine the models used to predict the future; to understand processes and linkages in the climate system not yet identified (or to improve understanding of such processes so they can be accurately inserted into predictive models); and can be used to assess the predictability of climate relative to noise in the system. As we move into a climate outside that used to tune and test models, it is important that models demonstrate their skill in reproducing known features of an extended range of climate states seen in the palaeo record.

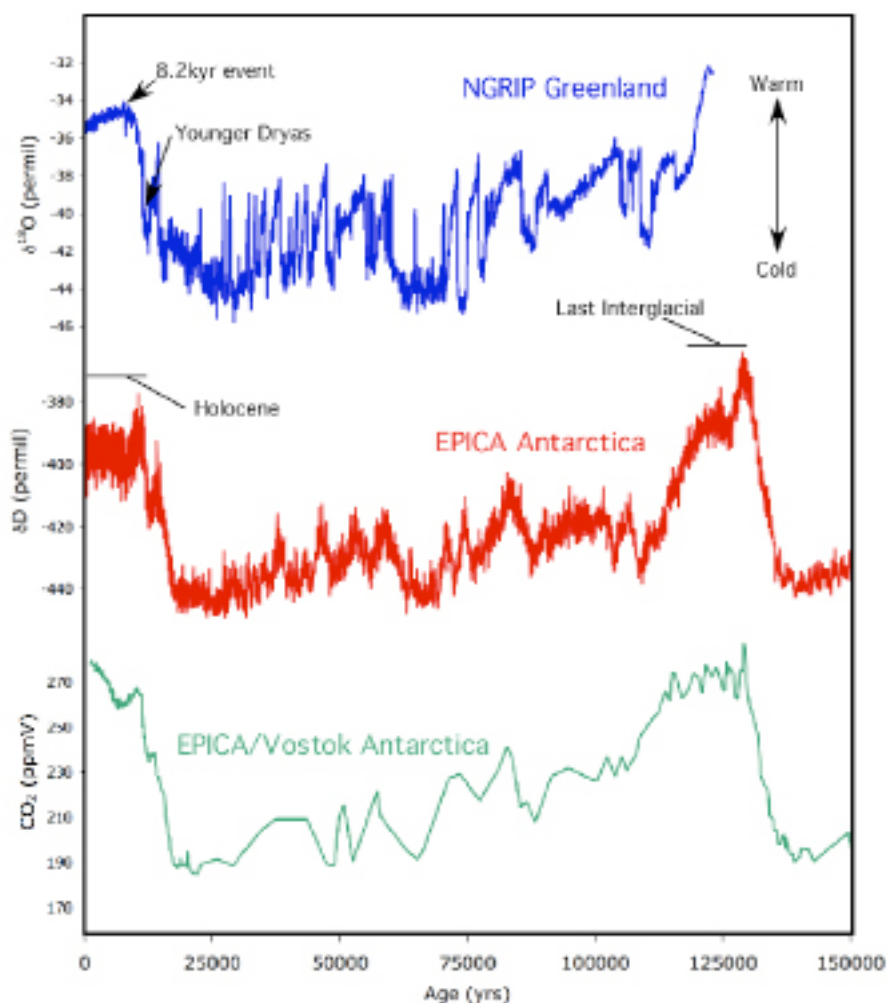
This White Paper identifies eight climate issues where palaeoclimate data has greatest ability to reduce future uncertainty. For each of these eight issues, uncertainties identified by the IPCC are listed, examples of palaeoclimate successes described, and the potential for further palaeoclimate work laid out. This paper is not intended to be an exhaustive review of palaeoclimate research, but rather to illustrate the power and potential of such research to the specific question of future climate prediction with a limited number of examples.



These examples indicate the power of palaeoclimate to complement modelling and present-day observations in science's quest to understand the response of the climate system to anthropogenic forcing.

B1	Palaeoclimate archives show coherent regional changes in precipitation in different climate boundary conditions, including many regions where models disagree widely about precipitation change.
B2	Tree-ring records extend regional drought records through the last millenium and beyond allowing assessment of the pattern and frequency of drought events.
B3	Dated marine terraces provide clear evidence that sea level was 4-6m higher than today at the last interglacial under conditions slightly warmer than today, and recent data has suggested the rate at which sea level can rise to this height from modern levels.
B4	Ice-cores have quantified the history of atmospheric CO <sub>2</sub> and methane concentrations of the past 800 kyr, and the relationship between these gases and global temperatures.
B5	Comparisons of palaeoclimate data for the Little Ice Age with models driven by solar, volcanic and anthropogenic inputs have assessed the role of these forcings during this event and to climate more generally.
B6	Diverse palaeoclimate records have demonstrated the existence of large and rapid switches in Atlantic overturning, and the climate response to these switches on hemispheric and even global climate.
B7	Corals and other palaeoclimate records have demonstrated the sensitivity of ENSO to modest changes in boundary conditions during orbital change (Pleistocene) and warming (Pliocene).
B8	Arctic temperatures have been quantified for many times in the past, demonstrating extreme polar warmth during the Cretaceous, Eocene, etc. and the conditions during the last interglacial that led to significant melting of Greenland.

**Table 1:** Examples of discoveries from palaeoclimate with direct relevance to future prediction. A single example is taken from each section of Part B. Those sections also contain other examples, and a fuller referenced and illustrated description of these successes.



**Figure 1.** Ice core records of Greenland temperature (upper panel; NGRIP Members, 2004), Antarctica temperature (middle panel; Jouzel et al., 2007) and atmospheric CO<sub>2</sub> (lower panel; Petit et al. 1999, Monnin et al. 2001) for the last 150kyr. Ice core data such as this has played a significant role in knowledge of the linkage between CO<sub>2</sub> and warming, and about the possibility of abrupt change in the climate system. Some key intervals mentioned in the text are labelled.

## A2. APPROACHES TO THE APPLICATION OF PALAEOCLIMATE TO FUTURE PREDICTION

Part B of this White Paper details a number of questions where palaeoclimate data can help to improve prediction of future climate. Three methodological approaches are common to many of these questions. Recognition of the utility of these approaches, and their co-ordinated use, would enhance the use of palaeoclimate to solve uncertainties identified by the IPCC.

### *i. Quantifying proxy uncertainty and interpretation*

Interpreting the past relies on the application of palaeo-proxies. As with any climate observation, such proxy observations require knowledge of uncertainty. Uncertainties on the analytical measurements underlying palaeoproxies are generally straightforward to assess and are routinely quoted in the palaeoclimate literature. Uncertainty in the conversion of these proxy measurements into an environmental variable is harder and often not thoroughly assessed. Despite its importance, careful calibration of a palaeoproxy and assessment of its uncertainty can appear less exciting to a researcher or a funding panel than the application of this proxy to a palaeoclimate question.

Accurate calibration of proxies, including assessment of their limitation and uncertainties requires specific research effort. Such work involves the collection of dedicated sample sets across strong environmental gradients, the assessment of competing environmental effects on proxies, and the blind application of proxies to known changes to assess accuracy. Such work can also benefit from a multi-proxy approach where two or more proxies for the same variable are assessed relative to one another so that their agreement (or lack of it) provides an estimate of the structural uncertainty. And uncertainty estimates can be aided by inclusion of proxies in relevant models so that the impact of competing effects can be systematically investigated in a fully-coupled system under imposed climate changes.

Modelling of proxies offers particular insight where the proxy is controlled not by variation only at the site of measurement, but by conditions elsewhere. In such examples, forward modelling of the proxy tracer within the model provides a significantly improved approach to data-model comparison than comparison of proxies with model output of direct climate variables at single sites. A good example is the forward modelling of oxygen isotopes ( $\delta^{18}\text{O}$ ) in the hydrological cycle. Oxygen isotopes are used in many palaeoclimate archives (e.g. marine carbonates, stalagmites, lake records, ice-cores) to derive information about a number of variables (e.g. temperature, rainfall, salinity). Interpreting these records requires information about the controls on  $\delta^{18}\text{O}$  at sites of proxy measurement due to changes elsewhere, and is best achieved by insertion of  $\delta^{18}\text{O}$  directly into all the hydrological components of a climate model (Hoffmann et al., 2003; Schmidt et al., 2007; Tindall et al., 2009). All other proxies that rely on the chemistry of the water or vapour in which they form also benefit from such forward proxy modelling, for example carbon isotopes (Butzin et al., 2005), and Pa/Th in the ocean (Siddall et al., 2007). Although such forward modelling has been pursued successfully in some cases, advances are frequently lost as models evolve. Recognition of the value of such proxy modelling and the mainstreaming of this approach in UK modelling efforts will yield significant rewards.

### *ii. Synthesis of palaeoclimate data*

Combining models with palaeoclimate data requires construction of data syntheses to create suitable boundary conditions, define forcings and, crucially, provide coherent targets for model-data comparison. Systematic data synthesis also provides direct insight by bringing together disparate data sets into a coherent whole, and can help to identify new research directions.

Huge amounts of palaeoclimate data is generated internationally from many archives using diverse proxies. For instance, the American Geophysical Union has a section, Paleoceanography and Paleoclimatology, which

routinely attracts many hundreds of contributions at meetings (e.g. 844 abstracts at the Fall AGU meeting 2008). Lack of synthesis of this wealth of data means that, despite its potential use to refine future climate predictions, much of it is lost in the literature and never put into a broader context.

The potential benefits of synthesis of palaeoclimate data is shown by the BIOME 6000 dataset which reconstructs vegetation 6,000 years ago based on 1,800 pollen records ([http://www.bridge.bris.ac.uk/projects/BIOME\\_6000](http://www.bridge.bris.ac.uk/projects/BIOME_6000)) and by the NESDIS North American Drought product that synthesises USA tree-ring data to provide annual-resolution data on drought severity for the last 2,000 years (<http://www.ncdc.noaa.gov/paleo/pdsi.html>).

Data synthesis is not simply data management. Providing products for modelling requires compilation of data from many data archives, while taking account of data uncertainty, timescale uncertainty, irregular distribution of records, and the complexities of palaeoclimate proxy interpretation. These tasks make palaeoclimate synthesis significantly different from the task of data management conducted in NERC's existing data centres. Successful synthesis requires detailed knowledge of the records being synthesized (including the proxies and chronometers used); familiarity with the requirements of climate models; and the IT expertise to manipulate and present data effectively. A synthesis strategy must bring together these diverse areas of expertise in a sustained manner to build and maintain synthesised palaeoclimate products in appropriate formats for modellers.

### *iii. Testing model predictions against palaeodata*

Models used to predict the future can be tested by their ability to reconstruct past conditions. At its simplest, this approach involves forward modelling of climate under relevant changes in boundary conditions and comparison of the output with palaeo observations. Where significant mismatches occur, failure of the model is identified which might indicate structural error in the model (missing or incorrect processes), poor parameterisation in the model, errors in the data (or their interpretation), or a mis-specification of the appropriate experiment. When applied to a specific aspect of the climate system this approach can be used to assess the relative robustness of future predictions from different models. For instance, an ice-sheet model that fails to predict past Greenland ice volumes reasonably, might not be likely to predict future condition on Greenland.

A more statistical approach to quantify the uncertainty in future climate change predictions is to assess those predictions in the form of probability distribution functions. This technique involves the production of an ensemble of possible model predictions of the future, often by varying uncertain parameters in the model which control the strength of physical, biological and chemical feedbacks. This "prior" distribution of outcomes is then weighted by assessing the skill of each model version in simulating aspects of present day mean and historically observed climate change (Knutti et al., 2006; Murphy et al., 2004; Piani et al., 2005). The resulting weighted or posterior distribution then forms the climate prediction. The key assumption in the approach is that the skill in simulating the climate of the present day and recent past translates into skill in simulating future climate states.

A limitation of this approach is that the range of climate conditions observed in the instrumental record is small compared to predicted future change, and does not capture long-term processes and feedbacks. The use of palaeo-climate data in determining the weights in such probabilistic prediction systems may allow these limitations to be overcome. This approach has been suggested in a handful of studies (e.g. Annan and Hargreaves, 2006; Schneider von Deimling et al., 2006) and is currently being investigated in the UK in the QUEST-funded PalaeoQUMP project and within climateprediction.net (Muri et al., 2007). This approach has tremendous potential to decrease uncertainty for aspects of the climate system (including those relevant to particular regions) where models presently disagree and where changes in the instrumental changes are small compared to possible future change.

### A3. RECOMMENDATIONS

Many aspects of past climate are interesting from a pure-science perspective. What did the world look like in the past? How did climate operate when conditions were very different from today? Such curiosity-driven questions have provoked (and will continue to provoke) deep insight into the functioning and history of the Earth system. Such research has a long history of funding by NERC through responsive-mode mechanisms.

This white paper argues that, with the present need to better predict future climate, palaeoclimate also has an important applied-science aspect. Assessing the behaviour of the climate system under boundary conditions that differ from today's, or on timescales longer than observed in the instrumental record, relies on palaeoclimate observations and on appropriate modelling. Such applied palaeoclimate research should form part of NERC's strategic research programme portfolio.

In Part B (and summarized in Table 2), we provide examples of specific questions where climate uncertainty identified by the IPCC AR4 can be addressed through suitable application of palaeoclimate approaches. This work involves new measurements, new calibrations of proxies, data synthesis, and model-data comparison. In general, palaeoclimate approaches should be fully integrated into NERC's efforts to improve prediction of future climate. We make four recommendations as to how this can be achieved:

#### *i. Develop a NERC strategy for palaeoclimate data synthesis*

Synthesis of palaeoclimate data in a format and manner useable for model/data comparisons is essential to make full use of such data (see Section A2 iii). A synthesis strategy must bring together skills from several disciplines to build specific expertise in palaeoclimate data synthesis, which must then be maintained through appropriate sustained support. The goal of the strategy would be to build and maintain a range of synthesis products to draw maximum potential for model refinement from the broad range of available palaeoclimate data. The need for sustained specific expertise and for continued synthesis efforts suggest that this strategy might best be realized through a dedicated palaeoclimate synthesis centre.

#### *ii. Decrease uncertainty in future projections through explicit use of palaeoclimate data*

UK models used for prediction of global and regional future climate should be routinely assessed against palaeoclimate data to assess their validity and reduce uncertainties in future projections (see Section A2 ii).

#### *iii. Integrate palaeoclimate data into new thematic programmes*

Palaeoclimate can and should contribute to Climate- and Earth-System-Science-related NERC research programmes, including those presently being planning (e.g., The Changing Water Cycle; Ocean Acidification; Arctic Research). To ensure this, those devising theme actions and calls should ensure that questions motivated by palaeoclimate are explicitly included in the top level goals of each new programme. There is a danger, however, that pursuing this approach alone would lead to fragmentation and failure to realize the potential of palaeoclimate. This could be prevented by overall coordination of the development and application of palaeoclimate data to earth and environmental problems. Such an approach would allow a more cohesive strategy to be developed on the use of existing NERC investments such as IODP and QUEST.

The US-NSF programme, Paleo Perspectives on Climate Change (P2C2) acts as such a co-ordinating programme for palaeoclimate within the US climate research portfolio and offers a possible model. Some of its goals are similar to those outlined in this White paper, including its two major foci: "1) Provide comprehensive palaeoclimate data sets that can serve as model test data sets analogous to instrumental observations; 2) Enable transformative syntheses of palaeoclimate data and modeling outcomes to understand the response of the longer-term and higher magnitude variability of the climate system that is observed in the geological record." ([http://www.nsf.gov/funding/pgm\\_summ.jsp?pims\\_id=5750&from=fund](http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5750&from=fund)).

#### *iv. Provide cross-disciplinary training*

A continued problem is the different “languages” and approaches of the modelling and palaeo-data communities, and of the climate and palaeoclimate communities. Efforts to improve “translation” should include integration of modellers and those making palaeo-observations at NERC summer schools; and increased connection between the Hadley Centre and those in the wider NERC community researching palaeoclimate.

Section	Palaeoclimate potential
B1	Reduce uncertainty in predictions of future tropical rainfall by ensemble modelling against 6 kyr and abrupt change palaeoclimate data.
B1	Improve regional and local modeling accuracy by comparing downscaled model results to specific sites of palaeoclimate data.
B2	Assessment likelihood of future droughts by extending tree-ring drought records to highly populated regions such as south-east Asia and China.
B2	Use new archives (e.g. stalagmites, rapidly accumulating sediments) to assess relationship between storm events and climate state.
B3	Confirm existing palaeo-records that indicate sea-level rise from present levels at a much more rapid pace than predicted by IPCC.
B3	Use existing and forthcoming ice-core data to test the new generation of ice sheet models against conditions at the last interglacial.
B4	Use palaeoclimate to assess size and direction of carbon cycle feedbacks which are too slow and geographically disperse to assess with modern measurements.
B4	Assess the response of the carbon cycle to rapid changes in carbon fluxes by study of past abrupt changes (such as the Palaeocene-Eocene Thermal Maximum).
B5	Use high-resolution palaeoclimate data to assess and quantify links between solar output and climate change.
B5	Use palaeoclimate records to assess feedbacks between climate and aerosol production from terrestrial and ocean ecosystems.
B6	Improve palaeoproxy calibrations to better quantify the range in Atlantic overturning circulation possible in different climate states.
B6	Expand the synthesis of ocean palaeodata to provide boundary conditions for models, particularly in the data-poor Southern Hemisphere.
B7	Increase density and quality of past ENSO records to characterise responses to changing boundary conditions.
B7	Forward model oxygen isotopes in climate advanced general circulation models, so models can be directly compared with marine, ice core and stalagmite records.
B8	Assess relationship between permafrost occurrence and climate, including implications for methane release and Arctic nutrient supply.
B8	Reconcile models against periods of polar warmth in the past to provide some confidence in predictions for the magnitude of future high latitude warming.

**Table 2:** Examples of the potential of palaeoclimate to provide insight into the operation of the future climate system. Two examples are taken from each section in Part B, where further information about these issues is provided. These examples are illustrative and are not proposed as an exhaustive list of potential applications of palaeoclimate to future prediction.



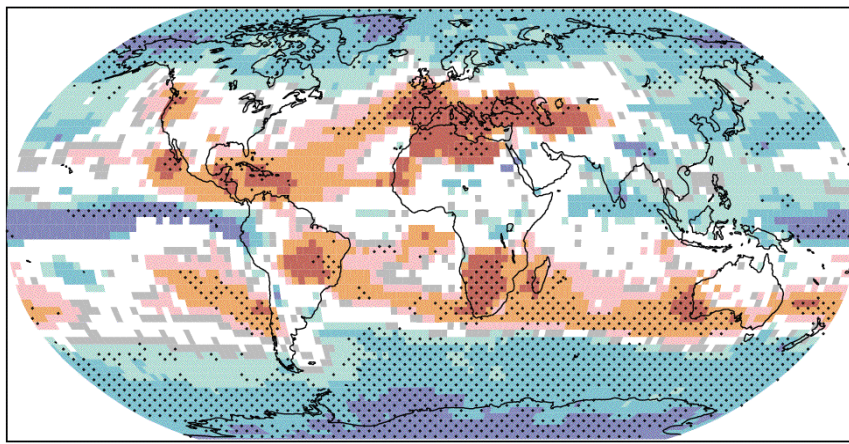
## PART B: THE DETAILS

### B1. TROPICAL AND SUB-TROPICAL RAINFALL

Tropical rainfall provides water for the majority of the world's population, and its variability causes floods and droughts with severe social consequences. Predicting change in tropical rainfall involves understanding of monsoon and ENSO dynamics and remains a significant challenge.

#### *Uncertainty identified by IPCC*

Changes in tropical and sub-tropical rainfall regimes are predicted in all models in the IPCC AR4 archive. Unfortunately, in many specific regions the changes projected by these models cover a huge range, with different models disagreeing even on the sign of future change (Fig. 2). This is particularly important in the key areas of sub-Saharan Africa, India and China - home to billions of people, and with large vulnerabilities to rainfall anomalies.



**Figure 2.** Multi-model average changes in northern-hemisphere-summer precipitation for the period 2090-2099. White areas are those where less than 66% of models agree about the sign of the change, stippled areas are where more than 90% agree (IPCC AR4)

#### *Success of palaeoclimate*

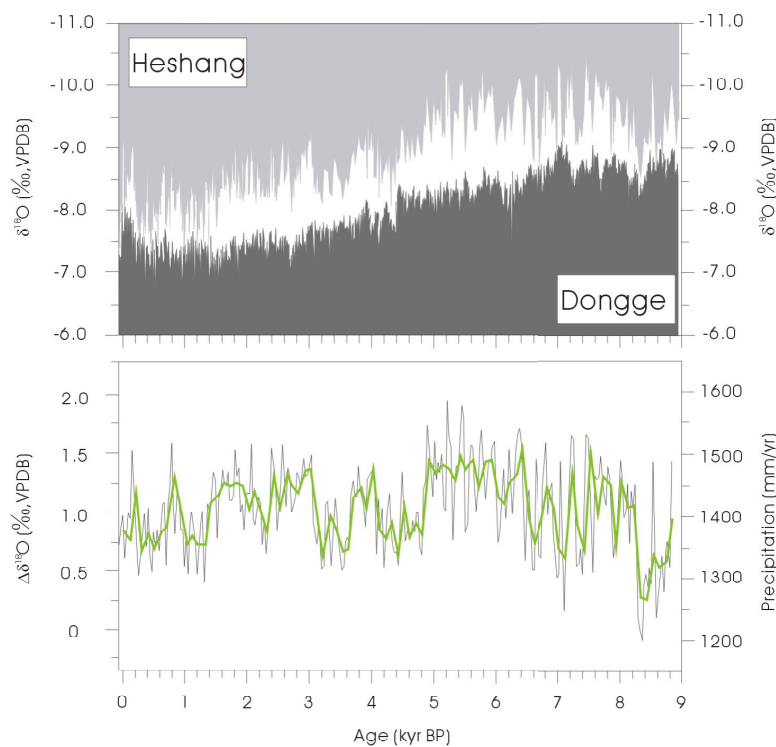
Palaeoclimate records associated with the hydrological cycle in tropical regions where future predictions are uncertain show coherent and significant changes through time, demonstrating the climate system response to external forcings. In the Early to Mid-Holocene, lake levels in northern Africa, India (and to some extent China) are all higher, in concert with a shift towards warmer Northern Hemisphere summers due to the influence of precession on seasonal solar insolation. Other tracers of the hydrologic cycle, such as water isotopes recorded in speleothems (Fig. 3) and ground waters show large amplitude variations, again coherent with orbital forcing (Wang et al., 2008) and with episodes of particularly cool North Atlantic temperatures (Wang et al., 2004). Vegetation changes consistent with these hydrological shifts are seen in pollen records in the Sahara and further afield (e.g. Edwards et al., 2000; Harrison and Prentice, 2003).

Records of tropical rainfall during the 6kyr BP period have been targeted for data synthesis and for co-ordinated model experiments, including by some IPCC models used for future scenarios. Such models generally show increases in rainfall in the appropriate places but with insufficient magnitude to match the inferred past vegetation changes. More recently, the forward modelling of water isotopes in precipitation (e.g. Schmidt et al., 2007) has started to show good matches between models and data from cave records.

## Future perspectives

The quality of palaeo data for the 6kyr BP period now makes comparison of data with palaeo-model-runs directly usable in weighting future projections made with the same models. Further model simulations should use boundary conditions that are as close to the conditions at 6kyr BP (including known vegetation changes, dust changes, and remnant ice sheets in North America) as possible and have been proposed in the next phase of PMIP (<http://pmip.lsce.ipsl.fr/>). Ensemble runs with individual models and inter model comparisons should both be compared with 6kyr data to reduce uncertainty on future model predictions of tropical rainfall. Similar data-model comparison could also be pursued for abrupt millennial scale rainfall changes, and for other periods.

At a regional level, more work is needed to understand how to downscale model changes to specific sites and specific proxies. Regional modelling, and the direct inclusion in modelling of proxies such as oxygen isotopes will enable this goal to be met, so that powerful palaeo-archives of past rainfall can be used to understand the pattern of precipitation change as climate boundary conditions change.



**Figure 3.** An example of rainfall reconstruction for the Holocene using oxygen isotope records from stalagmites (Hu et al., 2008; Wang et al., 2005). The upper panel shows two high-resolution records 600km apart in central China. The records show coherent changes and indicate low  $\delta^{18}\text{O}$  around 6 kyr (note inverted y-axis scale) indicating a stronger East-Asian monsoon during this period, and a short increase in  $\delta^{18}\text{O}$  at 8.2 kyr indicating decreased monsoon rainfall in response to abrupt Northern-Hemisphere cooling. The difference in  $\delta^{18}\text{O}$  between the two sites – shown by the grey line (and green smoothed line) in the lower panel – also provides information specifically about the history of precipitation in the region of China between the two caves.

## B2. FLOOD, DROUGHTS AND CYCLONES

The basic need for water and food to sustain populations means that predicting the extrema of the hydrological cycle (e.g. droughts, floods and cyclones) and their impact on water supplies and agricultural sustainability during climate change is a pressing concern. Extremes in the hydrological cycle occur regionally, are a feature even of the last 10 kyr of stable warm climate, and have changed civilisations (deMenocal, 2001). Trends in instrumental records imply that, in some regions, there are increases in the occurrences of droughts and floods.

### *Uncertainty identified by IPCC*

The IPCC states that, “substantial uncertainty remains in trends of hydrological variables because of large regional differences, gaps in spatial coverage and temporal limitations in the data (Huntington, 2006).” And that, “Tropical cyclones, hurricanes and typhoons exhibit large variability from year to year and limitations in the quality of data compromise evaluations of trends.”

### *Success of palaeoclimate*

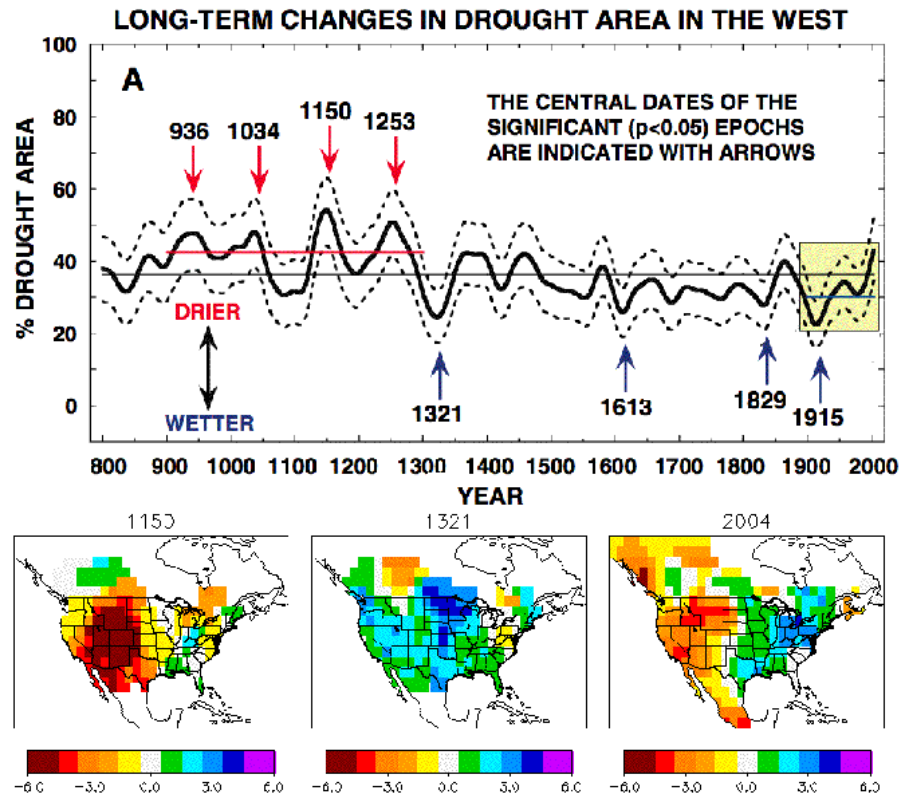
Instrumental records show that floods and droughts tend to characterize extrema of regional quasi-periodic ocean-atmosphere oscillations and, consequently, are susceptible to enhancement with global warming (Trenberth et al., 2003). In the Pacific, for instance, droughts in Australia are associated with El-Nino conditions (Nicholls, 2004); and in the Atlantic region severe drought in the Mediterranean region are correlated with NAO variability (Cullen and deMenocal, 2000).

Tree-ring data enables extension of observed 20th Century drought data to a longer time frame. A great success in this area has been the high spatial density of records collected in North America extending over many centuries with annual resolution, to allow regional construction of precipitation (at a 2.5° grid resolution) (Cook et al., 2004). This work allows extension of the Palmer Drought Severity Index (PDSI), commonly used to assess present drought conditions, into the past to assess the rarity of major 20th century droughts in the 1930s and 1950s. This data also allows the spatial pattern of drought events in North America to be established, clearly indicating the power of palaeodata to provide regional climate information relevant to future prediction.

The extension of drought and precipitation measures with palaeo-records demonstrates that the linkage between droughts and ENSO is a robust feature of the climate system over millennial timescales. Anomalous warming over the equatorial Pacific consistently leads to enhanced upwelling, La Nina-style conditions and drought in the Western United States, flagging the potential for more frequent droughts with anthropogenic warming of the Pacific SSTs (Cook et al., 2004).

Observations imply that variations in tropical cyclones, hurricanes and typhoons are dominated by ENSO and decadal variability, which result in a redistribution of tropical storm numbers and their tracks, so that increases in one basin are often compensated by decreases over other oceans. The extension of instrumental records of hurricane activity into the more distant past has been derived from sand layers deposited by storms behind barrier islands, changes in coral chemistry, Caribbean stalagmite isotope records (Frappier et al., 2007), and variations in tree-ring patterns growing in coastal areas. An example of such work is the 5000 year palaeorecord of hurricane activity based on storm deposits in a Caribbean lagoon which shows that extrema of hurricane activity may be modulated by the ENSO oscillation and by the west African monsoon (Donnelly and Woodruff, 2007). This record also demonstrates that high SSTs are not a prerequisite for inducing frequent and intense hurricanes.





**Figure 4.** Tree-ring derived records of drought conditions in the US. The upper panel shows the percentage of the western USA effected by drought for the last 1,200 years (Cook et al., 2004) while the lower panel compares the regional pattern of the PDSI during extreme dry and wet years from this palaeo record compared to a recent year from the instrumental record. (from <http://www.ncdc.noaa.gov/paleo/pubs/cook2004/cook2004.html>).

### *Future perspectives*

Droughts and floods are a common feature of the climate system and appear to be linked to ocean-atmosphere decadal oscillations. It is still necessary to understand whether the linkages are stable regionally, temporally, and with different climatic baselines. A goal is the quantitative prediction of extrema from monitoring of key aspects of the ocean atmosphere system. Tree ring records provide an example of a proxy that can be generated with sufficient density of data for regional assimilation of centennial records and comparison to models. Highly populated regions dependent on rainfall, such as China and south-east Asia are key targets for future data collection and for further assimilation of similar datasets.

Other archives with sufficient resolution to capture extreme events (e.g. stalagmites, rapidly accumulating sediments) are reaching sufficient maturity to allow assessment of relationships between storm events and climate state. Such approaches have particular interest in regions such as the Caribbean or Southeast USA prone to significant societal loss during extreme events, and increasingly to the UK as extreme rainfall events increase flooding.

### B3. ICE SHEETS AND SEA LEVEL

Rising future sea levels represent one of the most difficult climate changes to adapt to. The magnitude and rate of these changes are difficult to predict, partly because of the long timescales for ice-sheet evolution. Palaeo-observations may be the only way to constrain ice sheet models to improve projections of the ice-sheet component of future sea-level rise.

#### *Major uncertainty identified by IPCC*

The IPCC AR4 quantified projections of a moderate rise in certain components of sea level by the end of the 21st century, with a rather small error bar (18-59 cm from all scenarios). These estimates did not, however, include the uncertainty associated with possible changes in ice-sheet dynamics, because the IPCC authors felt that a basis in the published literature for including such an estimate was lacking; they therefore concluded that they could not set a true upper bound for sea-level rise due to changes in the Greenland and Antarctic ice sheets. This is one of the largest and most significant uncertainties in future climate projection, and one where palaeoclimate observation can play a major role.

#### *Success of palaeoclimate*

The last interglacial, around 130-120 ka ago, provides a first constraint. There is strong evidence from a number of sources that much of the Arctic was around 3-5° warmer than today (NGRIP Members, 2004; Otto-Bliesner et al., 2006) for at least a part of the past interglacial. Similarly, Antarctica appears to have been 2-3° warmer than present for some millennia (Jouzel et al., 2007). Sea level is estimated to have been 4-6 m higher (summarised in Rohling et al., 2008). These data confirm that, under sustained polar temperatures of the order expected in the next century under business-as-usual type scenarios, sea level rises of several metres did occur. However, the evidence also suggests that Greenland ice did not disappear entirely (Otto-Bliesner et al., 2006; Overpeck et al., 2006), thus also placing some data constraints on the range of model-estimate temperature required (Gregory et al., 2004) to cause a complete removal and suggesting that some of West Antarctica may have been lost.

There has also been considerable success in studying the history of some of the ice shelves in the Antarctic Peninsula that have been lost during the past few decades (Bentley et al., 2005; Domack et al., 2005; Pudsey and Evans, 2001). These findings offer a valuable perspective on the conditions under which such shelves may be vulnerable, and the impact of ice shelf loss on land-based glacier discharge.

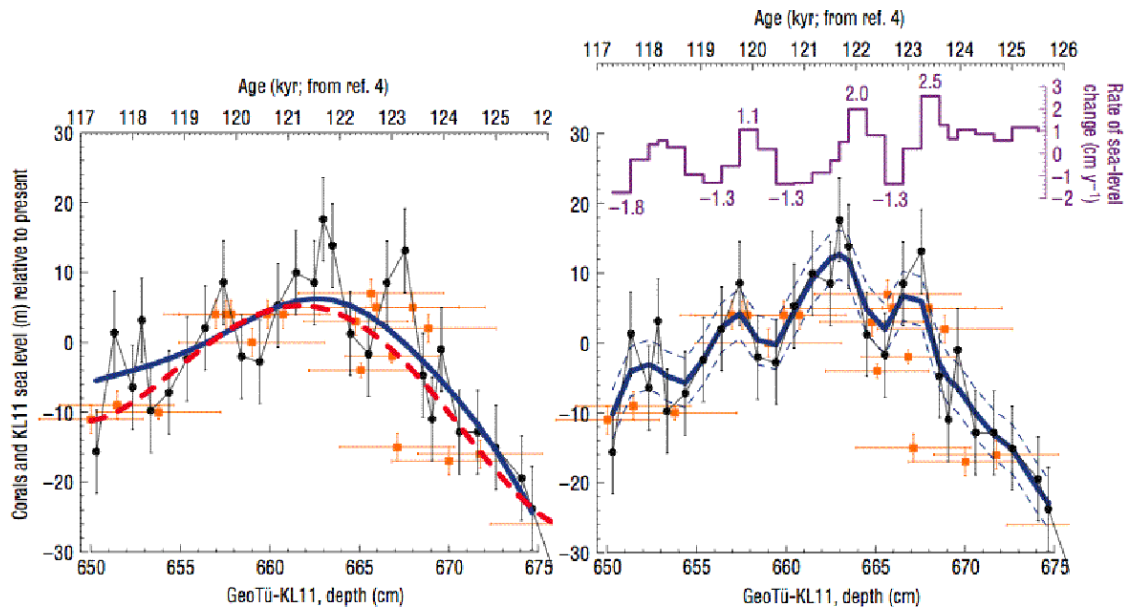
#### *Future perspectives*

There is still significant work to do to refine our understanding of the respective role of the Greenland and West Antarctic ice sheets for sea level during the last interglacial. A complete climate record for the last interglacial in Greenland ice cores has not yet been retrieved (but such a project, called “NEEM”, is underway with UK participation). Once this is available, and synchronised to the Antarctic climate record, it will provide a basis for attempting ice sheet modelling experiments based on last interglacial conditions with a new generation of ice sheet models.

Recent reports have indicated extremely fast rates of sea level change (up to 2.5m per century; Fig 5) into and within the last interglacial period (Blanchon et al., 2009; Rohling et al., 2008) using sediment stable isotope and coral chronology. These records suggest that sea-level rise from modern values can occur much more quickly than previously thought and need to be confirmed with additional observations. If these rapid changes turn out to be robust, they provide challenging targets for ice-sheet models, and carry important implications for future sea level prediction.

Data allowing assessments of the size of the ice sheets in the last interglacial are still limited. Ambitious drilling projects to determine the most recent exposure of bed material are feasible but challenging.

Longer timescales in the geological record offer the possibility to assess the conditions for stability of the Greenland and even the East Antarctic ice sheets. Model predictions of the conditions for ice sheet stability have focussed recently on CO<sub>2</sub> thresholds (DeConto et al., 2008; Lunt et al., 2008). It is difficult to make robust estimates of past CO<sub>2</sub> concentrations before the ice core period, but as an ambition, such measurements combined with derived records of past ice volume would indeed provide constraints that are highly relevant to a world with high CO<sub>2</sub>.



**Figure 5.** Sea level reconstructions for the last interglacial period from corals (orange) and Red-Sea oxygen isotope data (black) (Rohling et al., 2008) with various fits suggesting sea-level histories. At the degree of smoothing shown in the right hand panel, changes in sea level as high as 2.5 m per century are indicated, as shown by the purple curve above the data. If confirmed, such data suggests that sea level rise above its present level can be significantly faster than suggested in the IPCC AR4.

## B4. CARBON CYCLE FEEDBACKS

Increasing atmospheric CO<sub>2</sub> is the main driving force behind current and future projected climate change. The rate of this increase is dependant not only on our rate of fossil fuel burning but on a range of feedbacks in the carbon cycle. Such feedbacks also play a significant role in regional climate change through their influence on ecosystems, albedo and water budgets. Understanding these biogeochemical feedbacks in the carbon cycle is thus fundamental to the prediction of future climate change. Important aspects of this cycle operate on timescales that make palaeoclimate a powerful tool for better quantification.

### *Major uncertainty identified by IPCC*

The IPCC states that, “Models differ considerably in their estimates of the strength of the different feedbacks in the climate system”, and states that, “The magnitude of future carbon cycle feedbacks is still poorly determined”. The main uncertainties highlighted in AR4 include incomplete understanding of organic carbon production; the impacts of changes in ocean circulation on ocean CO<sub>2</sub> uptake; the response of marine biota to ocean acidification; the role and response time of terrestrial vegetation feedbacks; and our knowledge of the global methane cycle. Recent modelling studies show that uncertainty in carbon cycle feedbacks are as significant as physical uncertainties in controlling the future increase of atmospheric CO<sub>2</sub> (Huntingford et al., 2009).

### *Success of palaeoclimate*

Ice-cores have quantified the history of atmospheric CO<sub>2</sub> and methane concentrations of the past 800kyr, and the relationship between these gases and global temperatures. Other sedimentary, biological, and geochemical tools have extended this CO<sub>2</sub> record, albeit with much greater uncertainty, back to the Mesozoic.

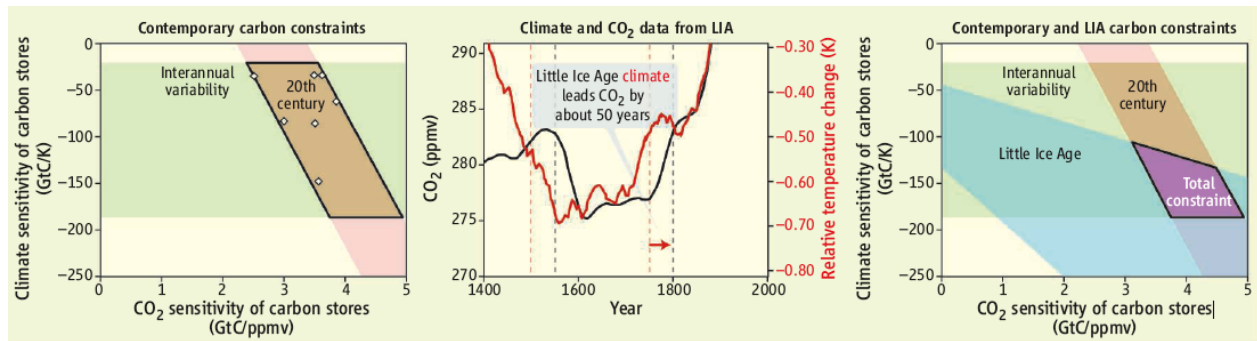
To a large extent, the representation of biogeochemistry in earth system and climate models rests on datasets generated from palaeo observations. Palaeoclimate has, for instance, indicated the possibility for substantial changes in regional vegetation cover (e.g. the grass-covered Sahara at 6kyr) and the possibility for abrupt changes in such cover (deMenocal et al., 2000). Palaeoclimate has also suggested the possibility for abrupt release of methane from clathrate deposits (Hesselbo et al., 2000) with potential significance for the future methane cycle. And it has identified the important role and consequences of ocean carbonate saturation state during periods of changing atmospheric CO<sub>2</sub> (Coxall et al., 2005).

### *Future perspectives*

Carbon-cycle models assessed by the IPCC disagree significantly about the response of the terrestrial biosphere to future change, with the future of the Amazon a frequently cited example. In this context, it is concerning that models presently find it very difficult to replicate changes in past vegetation which are known to have occurred from palaeo data. There is considerably more to be done in testing these aspects of the models against palaeodata to allow weighting of model relative to one another or within an ensemble, to perhaps improve certainty on future prediction.

More generally, there is uncertainty about the response of the carbon cycle to future change. Increasing atmospheric CO<sub>2</sub> levels cause a net increase in CO<sub>2</sub> uptake into terrestrial and ocean sinks, while increased warming tends to cause a net release of CO<sub>2</sub> back to the atmosphere. The size of both feedbacks remains uncertain, however, and cannot presently be reliably predicted by models. This limits knowledge about the future uptake of CO<sub>2</sub> from the atmosphere and therefore about the primary greenhouse forcing of climate change. Palaeoclimate data can provide useful constraints on the size of these feedbacks (e.g. Cox and Jones, 2008; Fig 6) and about how these feedbacks vary regionally and for different climate boundary conditions.

The past offers the chance to assess carbon cycle feedbacks during periods when atmospheric CO<sub>2</sub> approached values that are predicted to occur in the next century (400-1000ppmv, e.g. during the Pliocene, Oligocene, Eocene and Palaeocene). The timing, rate and mechanisms of major changes in the carbon cycle during such times are poorly understood but indicate threshold behaviour in the climate system that may not be replicated by the present suite of climate models. For example, it is unclear how fast, when and why the extreme event known as the Palaeocene-Eocene Thermal Maximum initiated. Investigating such warm climate threshold behaviour requires collection of a range of palaeoclimate data, including that from marine sediment coring (e.g. those collected by IODP, and IMAGES), ice coring, and through studies of pollen assemblage changes from terrestrial settings.



**Figure 6:** The use of palaeoclimate data (from the time of the Little Ice Age) to reduce uncertainty on the size of carbon-cycle feedbacks (from Cox and Jones, 2008). The left-hand panel indicates the possible range of net CO<sub>2</sub> uptake from the atmosphere due to temperature change (y axis) and atmospheric CO<sub>2</sub> change (x axis). This range is constrained (in brown) using information from today's interannual variability, and from CO<sub>2</sub> and T change of the 20th Century. The use of additional palaeoclimate data (CO<sub>2</sub> and temperature; middle panel) enables the range of possible sensitivities to be decreased as shown in the right-hand figure (in purple).

## **B5. EXTERNAL FORCINGS AND INTERNAL VARIABILITY**

Increasing atmospheric greenhouse gas concentration is likely to be a powerful forcing factor in future climate, but must be understood in the context of other possible forcing factors including orbital changes, solar variability, volcanic emissions, land-use changes, and a variety of aerosol effects. The latter induce radiative changes in the atmosphere and, particularly in the case of black carbon, also change surface albedo.

The inability to separate the importance of this range of forcings limits the attribution of climate change over the 20th Century. Changes forced by these external variables are also intertwined with changes generated by internal noise and feedbacks within the climate system, the level of which must be assessed for various climate states.

### ***Major uncertainty identified by IPCC***

Of the forcings external to the climate system, anthropogenic greenhouse gas emissions, orbital changes, and volcanic forcings are the best quantified. Others have undergone recent revision in scaling, such as centennial-scale solar variability – an area of understanding which remains based on physical models rather than direct observations thus limiting confidence (an issue explicitly identified in IPCC AR4). The magnitudes of other forcings are still only poorly understood and/or cover limited timescales. An example of the importance of developing knowledge in this area is the recent quantification of the importance of black carbon in northern hemisphere climate change (Shindell and Faluvegi, 2009). Non-linear coupling of these various forcings has not been investigated and their relative role, as opposed to that of intrinsic internal variability, is a source of uncertainty in attributions.

### ***Success of palaeoclimate***

Comparisons of observed patterns of temperature change with models driven by solar, volcanic and anthropogenic inputs have been used to assess the role of these forcings in past climate events and the general sensitivity of climate to such forcing. For the period 1650 to present, this approach has been pursued using direct observations of solar change, combined with palaeo data to quantify the volcanic forcing term and to map the pattern of northern hemisphere temperature change (Shindell et al., 2001).

The role of solar variability in causing climate change on timescales longer than any direct solar observations has been suggested by correlations between palaeo records of cosmogenic nuclide production and climate change (e.g. Wang et al., 2005; Fig. 7).

Techniques for reconstruction of past aerosol forcing are becoming increasingly mature and allow variations of aerosol loading during past climate events to be assessed. Past fire frequency has been assessed from incomplete products of combustion (including black carbon) preserved in sedimentary sequences (Lynch et al., 2007), and such data used to assess changes in biomass burning at the last glacial (Power et al., 2008) and to disentangle natural and anthropogenic influences on fire frequency over the past 2000 years (Marlon et al., 2008). Records of DMS oxidation products in ice-cores provide information about the marine production of aerosols during different climate states.

### ***Future perspectives***

Quantitative analysis of the impact of various forcings on climate, as conducted for the last few centuries in the northern hemisphere, should be extended into the southern hemisphere and further back in time, both of which requires additional proxy data.

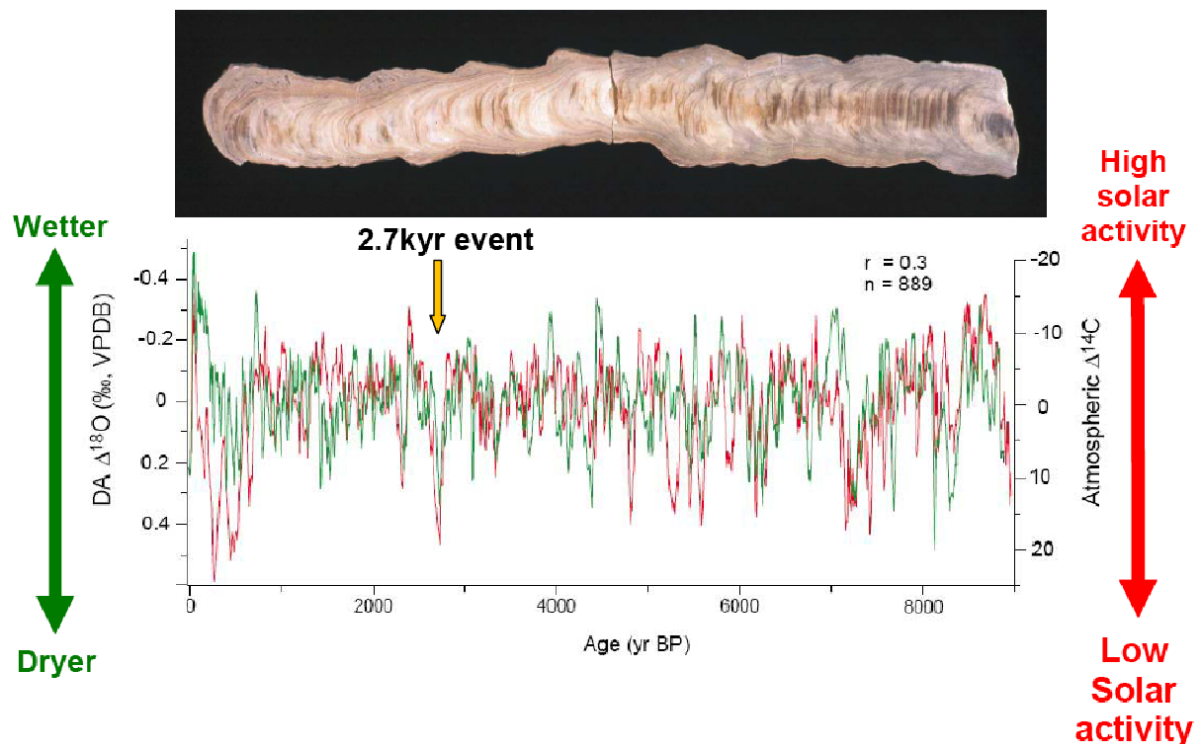


The use of cosmogenic isotopes to quantify total and spectral solar variability is uncertain because the relationship between the heliospheric magnetic field (which shields Earth from cosmic rays) and photospheric magnetic field (which modulates solar irradiance) is not known, and because the production and deposition (into a given palaeo archive) may contain a climate signal (Field et al., 2006). Recent change in our understanding in solar output variability has great implications for calibrating longer timescale cosmogenic isotope records in terms of total and spectral irradiance.

Links between solar variability and climate are most suggestive in speleothem data (Fig. 7) but require additional accurately-dated records and a focus on specific events such as that seen at 2,700 years BP to confirm this linkage and to assess regional sensitivities to solar forcing.

From an aerosol perspective, palaeo records of black carbon or DMS offer potential to assess feedbacks from changes in terrestrial and ocean ecosystems back into the climate system.

Statistical analysis of behaviour in the palaeo record around similar forcing changes, or for similar sets of conditions, will yield information on the intrinsic variability of the climate system, as well as on predictability and decadal regional variability. Comparisons between recent behaviour and data from earlier epochs could, in principle, reveal effects on regional climate of land use change in last millennium as they already have for anthropogenic greenhouse gas emissions.



**Figure 7.** Isotope data from a central Chinese stalagmite (in green) are dominantly controlled by the strength of Asian monsoon rainfall and are compared here with a record of atmospheric  $^{14}\text{C}$  concentrations from tree-rings (in red, note the inverted scale). Positive  $^{14}\text{C}$  values are caused by lower solar irradiance and at some times in the past (e.g. 2,700 years BP) show strong coincidence with periods of decreased Asian monsoon. Figure from Wang et al. (2005).

## B6. OCEAN CIRCULATION CHANGE

Ocean circulation plays a significant role in regional and global climate by its distribution of heat. Changing circulation also changes ocean uptake of carbon and the regional pattern of sea-level. From a UK perspective, meridional overturning circulation in the Atlantic (AMOC) is a particularly important aspect of ocean circulation because of its role in heat transport in the North Atlantic region and its known ability to change on a variety of timescales. Such change is possible for the future, with model projections suggesting  $\approx 30\%$  slower AMOC than present by the end of the 21st century (e.g. Schmittner et al., 2005; Schneider et al., 2007).

### *Major uncertainty identified by IPCC*

The IPCC 4AR recognizes limitations in ocean sampling (particularly in the Southern Hemisphere) which leave decadal variations in global heat content and regional salinity patterns insufficiently constrained. There is low confidence in the evidence for trends in AMOC related to changes in the global ocean freshwater budget. And there is uncertainty about the role of ocean circulation in controlling future ocean carbon uptake and regional sea level. Model simulations used in IPCC also have significant problems with parameterising small-scale eddy effects and the proper functioning of sill overflows, and have a wide range of projections up to 2100.

### *Success of palaeoclimate*

Stommel (1961) first showed that thermohaline-driven flow in the ocean might theoretically exhibit multiple equilibrium states. A major success of palaeoclimate studies has been the demonstration of large and rapid switches in the AMOC that might be associated with such multiple equilibrium and that they have large impacts on hemispheric and even global scales.

Detailed palaeoceanographic time series have targeted periods of accelerated climate change and reconstructed the ventilation of deep water masses and changes in the overturning rate and flow speed of the deep waters (Fig. 8). Such time series demonstrate that the AMOC has varied considerably during the Pleistocene to cause natural climate changes of magnitude and rapidity far beyond the last hundred years of direct instrumental observations (e.g. Charles et al., 1996; McManus et al., 2004). The climate effects of such AMOC perturbations have been reconstructed using a wide variety of palaeoclimate records from around the globe. Such work has demonstrated major features of the Earth's climate such as antiphase temperature changes of the Northern and Southern Hemispheres in response to AMOC changes (Blunier et al., 1998; Broecker, 1998; Stocker, 1998); the importance of AMOC in controlling monsoon intensity (Wang et al., 2004; Wang et al., 2001); and a link between AMOC induced rapid climate change and atmospheric  $\text{CO}_2$  (Ahn and Brook, 2008).

A particularly relevant example for future climate is the 8.2ka cold event, the most prominent climatic event in Holocene portions of the Greenland ice-cores. This event provides good evidence for the relationship between freshening of surface waters and weakening of the AMOC in climate conditions much like those of today (Ellison et al., 2006; Kleiven et al., 2008). A hierarchy of climate models has been used to test this relationship and assess the sensitivity of the ocean and atmospheric circulation to freshwater release (e.g. Alley and Agustsdottir, 2005; LeGrande and Schmidt, 2008; Renssen et al., 2002).

Very high resolution palaeoceanographic records have also allowed extension of modern observations of ocean circulation backward into the preceding millennium. For instance, variations in the near-bottom flow speed of Iceland-Scotland Overflow Water (ISOW) have been documented in a 230-year-long sediment record from the Reykjanes Ridge at (sub)decadal time scales (Boessenkool et al., 2007). Resulting ISOW flow is similar to observational hydrographic data where the records overlap and suggests a strong inverse coupling with the North Atlantic Oscillation index.



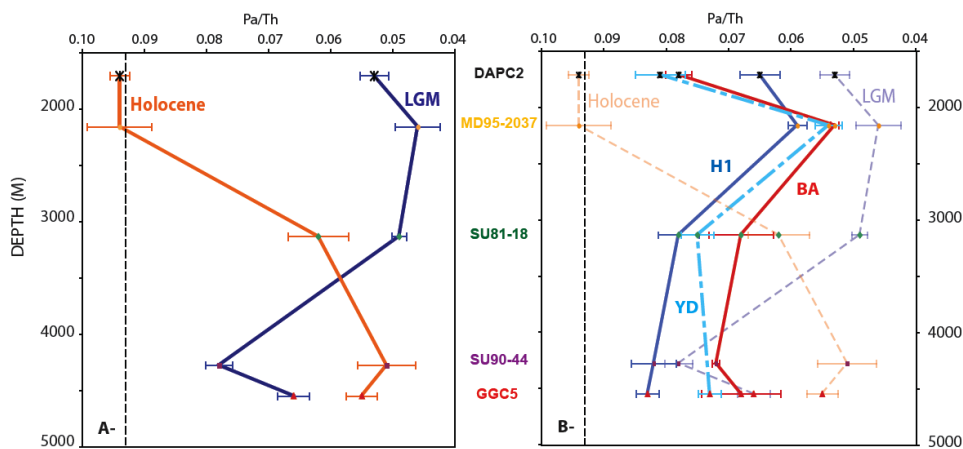
## Future perspectives

The relationship between ocean circulation and climate change can be better understood by further integration of palaeo-data and numerical models.

Palaeoceanographic proxies are not perfect reflections of one ocean parameter but are influenced by a range of effects. Improved development of quantitative proxies for key ocean variables can be achieved by specific study of these proxies in the modern ocean and against instrumental time-series, and by the inclusion of these proxies in appropriate models to better assess their response to changing condition. There will always be uncertainty in palaeoclimate records, however, and the level of this uncertainty needs to be better quantified and incorporated into modelling effort.

Palaeo-records are almost uniformly collected as time series, whereas models do well at producing spatial patterns of change over relatively short periods. Models remain under-constrained on longer time scales because of a lack of synthesis of palaeoceanographic data. Some global compilations for the last glacial maximum do exist (e.g. sea-surface temperature; MARGO project members, 2009) but expansion of these efforts to incorporate multiple parameters, wider time ranges, and better spatial data coverage (e.g. the Southern Ocean) will enhance their usefulness for improving future ocean predictability.

The past also offers a test bed for new ideas about the relationship between ocean circulation and other aspects of the climate system. For instance, there has been recent recognition that ice shelf stability on the west coast of the Antarctic Peninsula is sensitive not only to regional atmospheric warming but also to changes in ocean circulation, particularly intrusions of warm Upper Circumpolar Deep Water onto the continental shelf. The nature of such ice-ocean coupling is testable with appropriate palaeoceanographic records.



**Figure 8:** An example of the use of palaeographic data from marine sediments to derive depth-resolved information about the rates of past ocean circulation. The dashed vertical line represents the value for the Pa/Th proxy expected where there is no active flow. Lower values indicate faster flow (note the inverted scale). The left-hand panel compares the Holocene and Last Glacial Maximum flow for the deep North Atlantic region, indicating shallower flow during the LGM. The right hand panel also shows the changes in flow associated with millennial-scale change during the deglacial period, with the lowest flow observed during the H1 (Heinrich-1) event when conditions in the North Atlantic region were at their coldest (Figure from Gherardi et al., 2009).

## B7. THE EL NIÑO-SOUTHERN OSCILLATION (ENSO)

ENSO is the largest mode of interannual variability in the global climate system. The wide impacts of ENSO on regional climate, ecosystems and societies make it a key focus for both adaptation of society to short-term variability and as a dynamical component of longer-term change (e.g. through the role of tropical Pacific in possible Amazon die-back; Cox et al., 2002).

### *Major uncertainty identified by IPCC*

There has been significant progress in theoretical understanding of ENSO using new targeted observational platforms (e.g. the TAO array) and simplified models (Wang and Picaut, 2002). There has also been significant progress in the prediction of short-term seasonal variations in ENSO and its impacts using combined modelling and statistical techniques. Despite these successes, there is no consensus on how tropical Pacific mean-climate and ENSO variability might change as a function of increasing greenhouse gases.

The large inherent variability of ENSO makes it difficult to assess changes from the observed historical record. Were the two large ENSO events of 1982/83 and 1997/98 a consequence of, or exacerbated by, global warming or just part of the natural ENSO cycle? Have we now entered a period of reduced ENSO variability? With such a short record, it is impossible to apply techniques which simply extrapolate from the observed record (Stott and Kettleborough, 2002).

The number of interacting physical and biological processes (e.g. ocean upwelling, clouds and radiation, intraseasonal atmospheric dynamics, attenuation of sunlight by plankton) involved in the ENSO cycle present a continuing challenge to climate modelling. It is only the most recent generation of IPCC-class models that can consistently produce a spontaneous ENSO cycle and those models do so with a varying degree of success (AchutaRao and Sperber, 2006; Guilyardi, 2006). No model is able to simulate all the details of the ENSO cycle and some models may appear to have a good simulation of ENSO variability but have compensating errors.

The lack of any model consensus on the impact of global warming on ENSO, and the lack of a prospect of any simple theoretical approach, means that we must persist with approaches that combine observational data and complex climate models, with all their inherent uncertainties, in order to refine our best estimate of the impact of global warming on ENSO and its associated teleconnections/impacts.

### *Success of palaeoclimate*

The weak ENSO variability of the early-to-mid Holocene (6-9kyr ago) recorded in tropical corals (Tudhope et al., 2001); (Fig. 9) and other palaeoclimate records (e.g. Rodbell et al., 1999) suggest that ENSO is sensitive to modest variations in seasonality caused by changes in Earth's orbit. Efforts to understand the ability of ENSO to weaken in this way have examined a number of different hypotheses and models (Brown et al., 2008a; Liu et al., 2000) and helped to understand the behaviour of ENSO in altered boundary conditions.

The so-called mid-Pliocene "permanent" ENSO state (Bonham et al., 2009; Haywood et al., 2009; Molnar and Cane, 2007) more accurately described as a mean warming of the east Pacific relative to the west has motivated theoretical and modelling studies (Fedorov et al., 2006). This time period has been identified as a model-intercomparison case in the PMIP project because of elevated levels of CO<sub>2</sub> that make it highly relevant for future warming.

The reconstruction of ENSO variability in the last millennium, by joining together different coral records using techniques similar to those used in tree-ring studies (Cobb et al., 2003), provide reconstructions of past natural ENSO variability that may be useful for testing the long-term natural variability of ENSO in climate models.

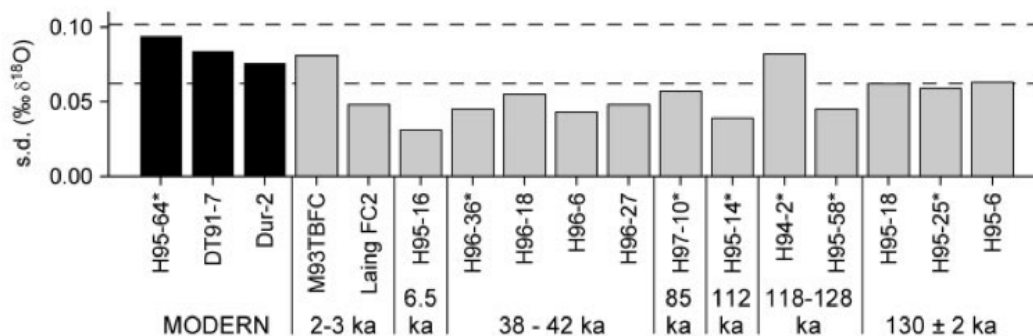
## Future perspectives

Palaeo-evidence for past variations in ENSO can continue to test both our fundamental understanding of ENSO and our climate models. Palaeo-data remains sparse, however and is often qualitative in nature. Our ability to recover palaeo-data with the annual resolution required to assess ENSO issues is increasing rapidly and now allows assessment of impacts of ENSO in many regions through analysis of coral, lake, stalagmite and other archives. New work on such archives should include improved calibration of the palaeoclimate proxies they record, the quantification of uncertainty on these proxies, and accurate chronology of the records.

Quantitative comparisons between palaeo-data and models are hampered by the present sparseness of data, by dating issues, and by mismatches between palaeo-archives and model output variables (Brown et al., 2008b).

In order to advance the use of palaeoclimate data in future climate predictions of mean tropical Pacific regional change, changes in ENSO variability, and changes in remote ENSO teleconnections, a number of activities would be useful. Data syntheses of palaeo records enable a more complete assessment of both models and palaeo-records. The forward modelling of palaeo-records would also makes quantitative data-model comparisons much more powerful as a tool for testing models. For example, one key diagnostic not included routinely in UK climate models is the transport and fractionation of oxygen isotopes, although such isotopes are a pivotal way in which information is extracted from many marine, terrestrial and ice records (e.g. Fig. 9).

There is a need to thoroughly link IPCC-related and palaeoclimate modelling of the ENSO system to ensure that the most up-to-date models are used in international inter-comparison activities and that lessons from palaeoclimate are incorporated into models used to predict future ENSO.



**Figure 9:** Variability of ENSO from fossil corals from the tropical Pacific (Tudhope et al., 2001). Each bar represents a time-series of oxygen-isotope data from a single well-dated coral, and is the standard deviation of the 2.5- to 7-year (ENSO) band pass-filtered isotope record. Horizontal dashed lines indicate maximum and minimum values for the modern coral records. Note that for much of the last interglacial cycle, ENSO variability has been lower than observed today, including that at  $\approx 6$ kyr in the mid Holocene when many climate boundary conditions (e.g.  $\text{CO}_2$ , sea-level) were similar to those today.

## B8. CHANGE IN POLAR REGIONS

Regions of the Arctic, as well as the Antarctic Peninsula, have been among the fastest warming regions of the globe in recent decades, and IPCC projects high northern latitudes to show the largest warming in the next century. This is expected to lead to a range of impacts, for example on sea ice, and potentially on the extent of permafrost and marine hydrates (which are implicated in storage or release of methane). Sea ice is projected to shrink in both polar regions, and an ice free Arctic in late summer is projected by many models by the end of the 21st Century or sooner. This has implications not only for climate feedbacks and ecosystems, but also in the economic and geopolitical sphere.

### *Major uncertainty identified by IPCC*

The importance of sea ice is widely recognized, and it represents an important feedback in the natural world and in models, though its influence on albedo, heat transfer, freshwater production, and transfer of trace gases (including CO<sub>2</sub>). Adequate data against which to test the long term accuracy of model sea ice reconstructions are sparse, however, limiting confidence in these models.

This is true in both hemispheres and particularly in the Antarctic where even observations of sea ice during the instrumental period are insufficient to allow conclusions to be drawn about the sea-ice trends.

The IPCC AR4 also identifies concern more generally about the ability of models to predict future temperatures at high latitudes because of the failure of the same models to be able to replicate the warm polar conditions observed on Earth during the Cretaceous, Eocene and Pliocene. IPCC states that this failure, “may indicate that high latitudes are more sensitive to increased CO<sub>2</sub> than model simulations suggest for the 21st century”.

### *Success of palaeoclimate*

A variety of palaeoproxies have provided quantitative knowledge of high latitude temperatures at times in the past including during more distant greenhouse periods (Jenkyns et al., 2004), the last glacial (de Vernal et al., 2005; Gersonde et al., 2005), and the last interglacial (Otto-Bliesner et al., 2006). Spatial distributions of palaeo-temperature provide good targets for models, with a notable modelling success being the ability to reconstruct the warmth of the interglacial in the Arctic region (Otto-Bliesner et al., 2006) (Fig. 10).

### *Future perspectives*

It remains challenging to reconstruct past sea ice but there is now potential for advances in both the understanding of sea-ice proxies and the integration of dataset from various methods with models. Sea ice extent can potentially be determined by a number of methods such as indicators of ice drift, specific markers such as whalebone, biological assemblages and biomarkers found in marine sediments, and by ice core proxies. All of these have difficulties in interpretation, and most would benefit from studies designed to understand and calibrate the strength of their relationship to sea ice extent. The use of different proxies (e.g. ice core and marine) in tandem to produce a consistent sea ice reconstruction is in its infancy, and such syntheses should be attempted seriously.

Such multi-proxy approaches would be useful for many questions with relevance to improved future prediction. Obvious first order questions are whether the Arctic was indeed ice free in the last interglacial, when the Arctic appears to have been 3-5° warmer than today, and in the early Holocene.

On land, accurate dating of periods of stalagmite growth at high latitude offers the potential to assess the relationship between permafrost occurrence and climate change. Such work would allow an additional test of





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